History of the Solar System

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ABSTRACT

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A brief introduction is given to the various approaches which have been followed in attempting to construct models of the origin of the solar system. The author then outlines in more detail one of the more recent approaches, involving models of a massive primitive solar nebula. In this approach a massive gaseous disk is first formed during the course of star formation, and the Sun must subsequently form from the disk as a result of hydrodynamical dissipation processes. Both the dissipation and the accompanying formation of the planets are estimated to require only a few thousand years. As a consequence, there was little time for the Earth to radiate its energy of gravitational accretion, and the primitive Earth must have been extremely hot.

RATIONALES AND APPROACHES

The history of the solar system is a subject which has perplexed scientists for more than three centuries, back to the time of Descartes (Ter Haar and Cameron, 1963). For the great majority of this time, there were few clues to guide scientific speculation. Several regularities were noted concerning the fact that the Sun, planets, and their satellites tend to have the same sense of spin, both with respect to rotational and orbital motion. Another regularity is the rough geometrical ratios of the orbital radii of the planets, a "law" associated with the names of Titius and Bode. The early speculators felt that they had to provide a mechanism through which the Sun could lose a rapid spin, although it is now known that this can easily occur through loss of angular momentum in the solar wind, independent of any processes associated with the origin of the solar system.

The scientific speculators discovered that these few observed facts provided them with an enormous degree of freedom. A wide variety of theories was proposed and subsequently discarded. These theories tended to fall into two classes: dualistic and monistic. Dualistic theories have supposed that the Sun interacted with another large body, as a result of which matter was torn out of the Sun to form the planets. This type of approach has now been abandoned for at least two decades. All present theories are monistic in character, in which the planets are assumed to be formed in the vicinity of the Sun by some process, often in association with the formation of the Sun itself. Most theories involve some sort of solar nebula, a large gaseous disk from which the planets have condensed. This type of picture was basically suggested first by Descartes himself, and

nearly everyone now subscribes to some form of primitive solar nebula. Perhaps the major exception to the following discussion is a theory proposed by Alfven and Arrhenius (1970a,b) in which the planetary bodies and their satellites are formed by condensation from a very low mass solar nebula continually renewed by plasma streams flowing through the solar system.

In general, two types of solar nebula have been discussed. Most theories of the origin of the solar system propounded within the last two decades have postulated what I shall call a minimum solar nebula. In this case the primitive solar nebula is characterized by arguing back in time from the present state of the solar system, a procedure which will probably appeal to those earth scientists who are fond of the principle of uniformitarianism. It is assumed that all of the non-volatile material present in the primitive solar nebula has been collected into the planets (see, e.g., Hoyle, 1963). The volatile material consists of two types, the hydrogen and helium with a mass about 300 times the abundance of rocky materials, and the water, methane, and ammonia with a mass about 5 times the abundance of the rocky materials. Thus, in order to obtain the minimum mass of the solar nebula, one multiplies the masses of the inner planets by a factor of about 300. Since Jupiter and Saturn appear to be close to the Sun in composition, ordinarily no correction factor is utilized for them. On the other hand, Uranus and Neptune appear to be composed mostly of rocks and the intermediate volatiles, so that a correction factor of about 60 might be required in their cases. When all of this mass is totaled, one has a minimum solar nebula containing about 0.1 of the mass of the Sun. It is a necessary consequence of this approach that the Sun must be assumed to form independently of the solar nebula, although perhaps at the same time.

The alternative approach requires that the Sun form from the solar nebula. This means that the solar nebula must contain at least one solar mass at the beginning. In fact, it must contain somewhat more mass than this. Young T Tauri stars, newly formed in space, are observed to be losing mass at a fairly prodigious rate, something like one solar mass per

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million years. Not all of the mass of the solar nebula can be dissipated to form the Sun, since a significant amount of mass must be left behind to store most of the angular momentum contained in the initial solar nebula. The initial nebular mass must be considerably greater than that of the Sun, probably of the order of two solar masses. This general concept may be described as the massive solar nebula. I have been perhaps the principal advocate of this type of model (Cameron, 1973; Cameron and Pine, 1973). The more quantitative developments of this theory are quite recent, and I shall concentrate on a description of them in the remainder of this article.

The motivation for proposing the massive solar nebula actually arises from considerations of star formation. If we believe that the formation of the planets is related to the formation of the Sun, then we can try to make our models of the primitive solar nebula consistent with what we know of star formation.

One of the most important areas of astronomy in which our knowledge has greatly increased in the last few years concerns the properties of the interstellar gas and dust. Young, newly-formed stars are observed to be associated with concentrations of the interstellar gas and dust in the spiral arms of galaxies. Relatively simple physical considerations indicate that stars cannot form singly under typical conditions in the interstellar medium, but only in groups, or associations, containing a total of a few hundred or thousand solar masses. This is comparable to the masses of gas which are clumped together to form interstellar clouds. Thus, in the modern theory of star formation, interstellar clouds undergo gravitational collapse, fragment into ever smaller units, and eventually these units form an association of young stars. Such associations are relatively short-lived; most associations of young stars are seen to be dispersing into space.

The fragments of the collapsing interstellar gas cloud are likely to have significant internal random motions, since they are formed by dynamically violent processes. Associated with these random motions will be corresponding random components of angular momentum which will be possessed by the collapsing fragments of gas. A typical fragment can be expected to have a large enough angular momentum so that when the collapse is completed, the result is a rotating disk of gas, resembling somewhat a flattened spiral nebula, which does not have a separate star formed at the center. This is the origin of the concept of the massive solar nebula.

PROPERTIES OF THE MASSIVE SOLAR NEBULA

Detailed numerical models of the massive primitive solar nebula have been constructed by Milton R. Pine and myself, utilizing the large computer at the Goddard Institute for Space Studies in New York. Two basic models have been constructed, corresponding to slightly different assumptions about the character of the fragment of the interstellar cloud which is collapsing to form stars. In one assumption, the fragment is assumed to be a uniformly rotating sphere, with a uniform internal density distribution; the gaseous disk which results when this sphere flattens in the direction parallel to its spin axis is called the

"uniform model". The other assumption assumes again that the fragment of the collapsing cloud is a uniformly rotating sphere, but in this case the internal density distribution is assumed to vary linearly from a central value to zero at the surface, and the flattened disk derived from this sphere is called the "linear model".

When a fragment of an interstellar cloud is collapsing at an initially low density, the heat released by the compression of the gas can readily be radiated away, since the gas is quite transparent. However, at a later stage when the density has become quite high within the collapsing fragment, the gases and their associated dust particles become largely opaque to the outflow of the heat released by the compression of the gases, and consequently the solar nebula which is formed from such a fragment can be expected to be quite hot, particularly near the center. The pressure and temperature along the mid-plane of the numerical models constructed by Pine and myself are shown in Fig.1.
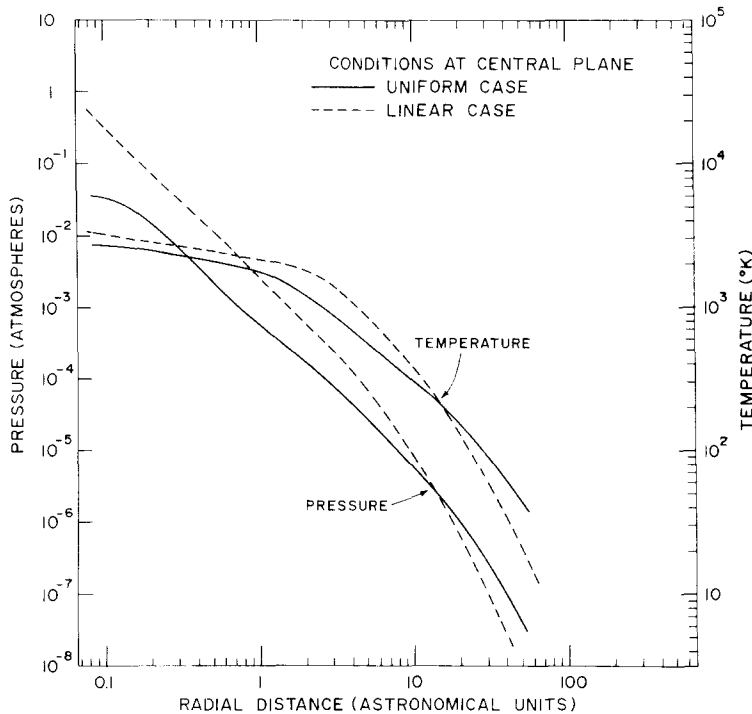

Fig. 1. Pressures and temperatures at mid-plane in the primitive solar nebula models of Cameron and Pine.

These combinations of pressure and temperature have some rather interesting implications for the chemical state of the material within the models of the solar nebula. It may be noted that the temperature becomes of the order of $3000°K$ near the center of the models, and hence there are no condensed solids within the solar nebula near the center. Farther out, the temperature can become much lower, and hence the condensed solids,

which were originally present in the interstellar medium as very small grains, would not be completely evaporated. Near the outskirts of the solar nebula the temperature is probably below 100°K, and under these conditions even the very volatile compounds, such as water, methane, and ammonia, will be present in chemically-condensed form. The detailed behavior of the primitive solar nebula depends upon these features of the condensed solids.

The internal structure of a typical numerical model is shown in Fig.2, in which are plotted on logarithmic scales the distance above mid-plane and the radial distance away from the spin axis of the nebula, in each case in astronomical units. It may be recalled that the mean distance from the Earth to the Sun is one astronomical unit. The structure is distinguished by the presence of convective regions, which are shaded, and non-convective regions, which are not shaded. A convective region is one in which the gas is vigorously stirred, and hence can efficiently transport heat to a radiating surface. In a non-convective region, the energy flow must occur by the radiant emission of energy, which can then be absorbed and re-emitted at a different location. There is a net energy flow down temperature gradients in such regions.

In the innermost shaded region shown in Fig.2, the temperature is sufficiently high that there are no condensed solids. On the other hand, the hydrogen is mostly in molecular form, and the temperature is high enough to start dissociating the hydrogen from the molecular into the atomic form. Most of the mass of the primitive solar nebula is composed of hydrogen, and this circumstance greatly favors the presence of convection within the medium. The upper convective boundary is determined by the condition that radiation emitted from that boundary can escape freely into space from either surface of the nebula.
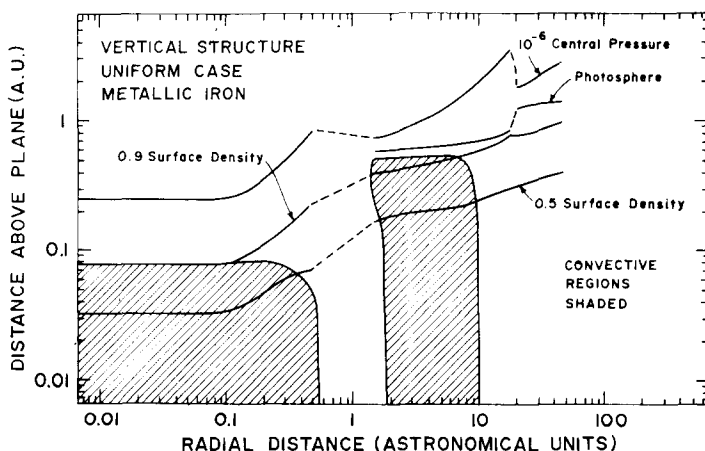

Fig. 2. The vertical structure as a function of radial distance in one of the primitive solar nebula models of Cameron and Pine.

Between the two convective regions the opacity of the gas is very low, since the temperature is sufficiently high that solids are still all evaporated. This region is not strictly one of radiative equilibrium, because the radiation is not fully absorbed at all wavelengths emerging from the center to the surface of the nebula.

The outer convection zone arises from the properties of condensed material. In this region the major condensates are rocky in character, including metallic iron and various types of silicates..The metallic iron absorbs electromagnetic radiation very readily, and the resulting high opacity of this region makes it convective. However, near the surface of the nebula there is a region in which convection has ceased and energy flow is by radiative transfer, until the final emitting surface, called the photosphere, is reached. This particular model has been constructed with the assumption that the iron is in metallic form at all temperatures at which it can be condensed. This is actually an extreme assumption, and assumes that the metallic iron is not in chemical equilibrium with the nebula at the lower temperatures. If it were in chemical equilibrium, it would appear mostly as troilite and iron components in silicates, and the resulting strong decrease in the radiative opacity would decrease somewhat the extent of the outer convection zone.

At distances beyond the outer convection zone the nebula is in radiative equilibrium. Even though the condensed solids are still present, the density of the medium is so low and its vertical extent is so large that convection cannot occur.

This structure is quite typical of the various models which were constructed by Pine and myself.

It is of considerable interest to estimate the rate at which the gases in the primitive solar nebula can be expected to dissipate, thereby leading to the formation of the Sun at the center of the nebula. According to the analysis by Pine and myself, the dissipation results primarily from the existence of internal circulation currents within the nebular models, which move radially outward at high altitudes above mid-plane, and radially inward near the center of the plane. These circulation currents arise in slightly different ways, depending upon whether the region is convective or not convective. In a convective region, it is a fundamental principle of the physics of a rotating fluid that the gas must rotate at a uniform rate on any cylindrical surface drawn about the spin axis. However, such a steady state is not possible here, because the force balance in the nebular model requires that the radial gas pressure gradient and the centrifugal force due to the rotational motion should oppose the gravitational potential gradient. Near mid-plane the pressure is highest, and hence the gas pressure gradient is also quite large, but near the surface of the nebula both the pressure and its gradient are small. Since the gravitational potential gradient does not change very much between these two locations, it follows that a force balance in the structure of the nebular model requires that the rotation rate of the gas, and the resulting centrifugal force, should be higher near the surface of the nebula than near mid-plane. Accordingly, uniform rotation on cylindrical surfaces is impossible, and a circulation current of the type described must be set up to compensate for this.

In a radiative region the situation is somewhat more complex, but again it is expected that circulation currents should exist in the same sense as in convective regions.

These circulation currents transport angular momentum outwards in the solar nebula. As the angular momentum at any radial distance in the nebula decreases, the corresponding rotational velocity of the material will decrease, and the mass will receive insufficient support against the gravitational potential gradient. Therefore, there is an inward flow of mass near the center of the nebula as an outward flow of angular momentum takes place. This is the basic process of dissipation which forms the Sun. The outermost parts of the solar nebula must act as reservoirs to store the angular momentum transported from the inner parts. Consequently the rotational motion of the outer parts of the nebula speed up, and hence there is an increase in the outermost radius of the nebula which accompanies the transport of angular momentum to that region.

Some very startling results emerge when the rate of transport of angular momentum is estimated. Near the center of the nebula, the bulk of the local angular momentum is expected to be lost in just a few years. In the region where the planets can be expected to form from the solar nebula, the time scale for removal of most of the angular momentum is a few thousand years. If these general conclusions are correct, then there are profound consequences for the formation of the planets. If solid material were to remain in fairly small sizes of bodies during the time in which the gases in the solar nebula are dissipating, then those solid materials would flow inward with the gases to form the Sun. After the Sun has formed, the large rate of mass loss associated with young stars will commence, and this can be expected to remove the remaining gases from the solar nebula. There is no reason to expect that collisions among small bodies, which may be left in space following the removal of the solar nebula, will lead to accumulation into larger sizes. Such collisions will tend to be rather violent, and the surfaces of the bodies can in general not be expected to be sticky. Thus it appears that the formation of planetary bodies requires the assistance of the gas in the solar nebula, and hence the major initial stages in the formation of such bodies should take place before the gas has dissipated. This places a very short time scale on the processes of formation of the major planets in the solar system.

ACCUMULATION PROCESSES

These considerations have led me to examine the processes by which solid materials can accumulate into larger bodies within the physical and chemical context of the primitive solar nebula models. I started with the collapse stage of a fragment of an interstellar cloud, which leads to the formation of the primitive solar nebula. The process of inducing gravitational collapse within the interstellar cloud should have been a fairly violent process, leading to internal turbulence within the collapsing cloud. It is a property of a highly turbulent gas that there are characteristic velocity differences across any characteristic length, and also that there are characteristic velocity differences at a given position within the fluid at two different characteristic times. These properties of a turbulent fluid are very important in considering the motion of the interstellar grains within that fluid. Such grains have typical dimensions between 0.1 and 1 microns, and at the low gas densities involved in the collapse of the interstellar cloud, they are only

relatively loosely coupled to the gas. Indeed, the turbulent motions of the gas accelerate the grains and establish characteristic grain velocities with respect to the local gas at any time. These velocities turn out to be of the order of 10 m per sec. Since these velocities are random, it is not surprising that they promote a rapid rate of collisions among the interstellar grains. The grains can be expected to be composed of all materials which condense at temperatures as low as about $10°K$. This means that all elements except hydrogen and the rare gases can be expected to be incorporated in the grains. They probably have a fluffy surface structure, so that in mutual collisions at velocities of about 10 m per sec, they will probably stick to each other.

Collisions among grains and accumulation of grains can be expected to continue all through the process of collapse to form the primitive solar nebula. My rough estimate is that the grains will have accumulated into bodies with radii of the order of 20 cm at the time the outermost parts of the solar nebula have been formed.

Let us first consider what is likely to happen in the outer parts of the solar nebula, where the gas temperature does not exceed $100°K$, and where the collections of interstellar grains retain the major volatile constituent, water (as ice). If accumulations of interstellar grains had not occurred, the grains would have remained suspended within the gas, and they would take millions of years to settle toward the center of the plane due to the forces of gravity. By that time the solar nebula would have dissipated and no large bodies would have formed.

However, the large accumulations of the grains can fall quite quickly through the gas toward the central plane of the solar nebula, and yet there is sufficient gas friction so that they do not noticeably overshoot the center of the plane. This brings condensed material toward a high concentration near the center of the plane on a time scale of the order of a century or less.

The large concentration of condensed bodies near mid-plane assists in further growth by mutual collisions. However, an even more efficient process is associated with the presence of the gas. The gas receives a partial support from the radial gas pressure gradient, but the condensed bodies do not receive this support. Therefore the condensed bodies must revolve around the center of the nebula more rapidly than the gas in order that the centrifugal force of the motion can entirely offset the gravitational potential gradient. In the case of the gas, a smaller rate of rotation is required because of the partial support by the gas pressure gradient. Hence there is a continual motion of the larger condensed bodies through the gas. If the bodies are very small, gas drag is sufficient to make the bodies move with the gas, but subject to a slow inward drift toward the spin axis of the nebula. The larger the body, the smaller the effects of gas drag, and the greater the velocity of the body with respect to the gas. There is a limiting velocity which these bodies can have with respect to the gas, which occurs when the bodies are quite large and gas drag effects are negligible; under these circumstances the bodies move through the gas with just the difference in rotational velocity which is required to offset the net inward force of gravity in the case of the body, or the result of the inward force of gravity and outward gas pressure gradient in the case of the gas. In the outermost parts of the solar

nebula, this relative velocity of the bodies with respect to the gas amounts to of the order of 100 m per sec.

This means that large bodies can rapidly sweep up the small bodies, since the large bodies are moving rapidly with respect to the gas and the slow bodies are moving only slowly with respect to it. I estimate that in this way bodies with radii of the order of 100 km can be built up in a time of the order of a few thousand years.

Once bodies grow to this size, an additional effect becomes important which makes the bodies grow even more rapidly in size. This is gravitational capture. The bodies are now massive enough so that the effect of the gravitational attraction of these bodies on solid material within the solar nebula is to cause that solid material to start raining down on the surface of the body once the solids come reasonably close. I estimate that this gravitational capture regime can cause the growth of planets the size of Uranus or Neptune in just an additional few thousand years. Thus the total time scale for accumulation of the outer planets is comparable to the expected time scale for dissipation of the solar nebula to form the Sun, which is a very satisfactory agreement of time scales.

Nearer the center of the solar nebula, but still outside the outer convection zone, conditions are slightly more complicated. Here the temperature exceeds $100°K$, and the icy constituents of the collections of interstellar grains evaporate. This will leave a rather fragile structure, but it can be expected that the condensed solids will again rapidly fall toward mid-plane in the gas, and there accumulate into larger bodies as a result of the effects of gas drag. When the growing bodies become large enough, gravitational capture should also accelerate their rate of accretion very markedly. However, at these somewhat smaller distances within the solar nebula, the space densities of solids are greater, and hence a more rapid rate of growth toward large bodies should become possible. Interesting effects should then occur when the solids, predominantly rocky in composition, have accumulated to form bodies containing several earth masses, perhaps 10 or 20 earth masses. Under these circumstances the gravitational field of the growing planetary body should become strong enough to commence a rapid capture of gas from the primitive solar nebula. This is again a progressive process, with infalling gas adding to the gravitational field of the planet, and causing an even more rapid capture of the surrounding gas. This process should probably continue until the gas in the solar nebula is locally depleted, and the infalling gas from farther away, due to the conservation of angular momentum, is forced to go into a spinning nebular disk surrounding the major planetary body. This is probably the way in which Jupiter and Saturn originated, and the systems of regular satellites of these bodies have presumably resulted from accumulations of solids within the gaseous nebulae formed about the planets.

Still farther inward in the solar nebula, in the region of the outer convection zone, the accumulation processes become still more complicated. The turbulent velocities in the gas serve to prevent solids from falling very close to the center of the nebula, and this reduces the rates of accumulation noticeably. Were it not for this inhibition, I estimate that accumulation processes would go on even faster in this region, once again leading to the formation of gas giant planets. However, in the time available for the formation of the

planets, a few thousand years, it does appear that bodies of the order of one earth mass in size can be formed. These bodies are not sufficiently massive to initiate a large-scale capture of gas from the nebula to become gas giants. Near the inner edge of the convection zone, where iron has condensed but magnesium silicates have not, it can be expected that a smaller iron-rich planet should be formed, and we can identify Mercury with this planet. The sizes of the accumulated bodies beyond the Earth continually decrease because of the decrease in the amount of material available for accumulation within the available accumulation time, so that Mars is considerably smaller than the Earth, and beyond Mars remains an unconsolidated swarm of bodies forming the asteroids.

Planets cannot be formed inside the region in which condensed material can exist, and this region approximately coincides with the inner edge of the outer convection zone. It may thus seem surprising, from an inspection of Fig. 2, that we should not expect to have planets formed inside about 2 astronomical units, whereas we know that the planet Mercury has a radial distance from the Sun of only approximately one-third of an astronomical unit. However, there is in fact no contradiction here, since in the primitive solar nebula the mass is very much spread out, and the gravitational potential gradients in the nebula are smaller than the present gravitational potential gradient in the solar system due to the Sun. When a massive body is formed in the primitive solar nebula, so that it is in approximately circular orbit in the nebula, then as gases flow past this body to form the Sun, the conservation of angular momentum of the massive body requires it to move gradually toward the forming Sun as the gravitational potential gradient steepens. Indeed, the formation of a planet such as Mercury near the inner edge of the outer convection zone will lead to an ultimate planet at about one-third of an astronomical unit after the Sun has formed.

When the Sun forms, the onset of its rate of rapid mass loss, called the "T Tauri phase", will remove the remaining gas from the solar nebula, thus terminating the more efficient of the accumulation processes within the nebula. This enhanced solar wind, of the order of 10^7 times as rapid a flow as the present solar wind, can also be expected to remove any primordial atmospheres retained by the inner planets from the primitive solar nebula. However, the massive atmospheres of the outer planets will be little affected by this strong solar wind.

THE HOT PRIMITIVE EARTH

We come now to another major consequence of the rapid dissipation of the solar nebula and the rapid formation of the planets. A tremendous amount of gravitational potential energy is released in the formation of a planet such as the Earth, and when the formation of the Earth takes place rapidly, a great deal of the released heat is unable to escape from the Earth by radiation from its outermost surface. This means that the Earth must have been exceedingly hot when it was first formed. The idea of a primitive hot molten Earth is not new, but the present calculations lead to an even more extreme conclusion. Most of the outer layers of the Earth will in fact be formed as a gas. Incoming

solid material will be heated so much when it falls upon the surface of the Earth that its infalling energy will be sufficient to vaporize the rock and metal constituents of the solids. This leads to an expectation that the primitive Earth should have an extended atmosphere composed of silicates and their thermal decomposition products. Metallic iron can be expected to have precipitated out from this very hot gaseous atmosphere.

At this stage the primitive Earth should have very little internal content of the more volatile elements. As such elements appear at the top of the gaseous silicate atmosphere, the interface at that level between the silicate atmosphere and the surrounding solar nebula should result in a vigorous convection of the adjacent solar nebula gases, which carries away the tremendous outpouring of heat from the forming planet. This convection should also carry away the lighter, more volatile gases brought in by solids to the accumulating Earth. If oxidized iron is present in the silicate atmosphere, it would probably be reduced upon exposure to this interface.

The existence of a hot silicate atmosphere must be only a very temporary phase in early Earth's history. The rapid rate of radiation from this atmosphere should allow silicates to re-condense in a time of about 1,000 to 10,000 years. Thereafter the Earth would be completely molten, but one can expect it to have separated out a core which contains metallic iron and possibly a considerable amount of iron sulfide. There has been a considerable discussion in the literature of the subsequent thermal history of such an Earth model.

The fact that the Earth at this stage has a very small content of the more volatile elements is perhaps a variation on these usual discussions of terrestrial history. The present calculations indicate that the volatiles should be brought into the Earth at a very late stage. At the time of formation of the Sun and removal of the remaining solar nebula, smaller solid bodies will be left stranded in space, and many of these will have orbits which will result in a collision with the Earth at a rate which falls off gradually over millions of years. These small bodies represent pure chemical accumulations of material, and they will have been in equilibrium with the primitive solar nebula gases. Thus they will never have been very hot, and they will bring volatile materials into the Earth as the latter sweeps them up. Much of the Earth's oceans may have been brought in as water of crystallization in such solid materials. The collision of the Earth with major cometary bodies may also have contributed to the water in the oceans. Perhaps the outer 10% of the Earth's mass may have been acquired in this manner. However, not all of the material thus finally swept up need have remained in the surface layers. The outer mantle of the Earth at this stage was probably convective, and hence the newly-acquired solids would be distributed throughout the mantle by these convective motions. Harold Urey (1952) has long maintained that the Earth must be formed "cold" because of the presence of these volatile materials; in the present picture only about 10% of the Earth is formed "cold".

There are two conceptual ways in which the Moon may possibly have been formed within the context of the present models of the primitive solar nebula. These conceptual methods take account of the strange bulk chemical composition of the Moon, which is

strongly depleted both in the more volatile elements and in metallic iron. It may also be strongly enhanced throughout in calcium, aluminum, and titanium, which are very rich in the upper layers of the Moon, provided this enrichment also extends very deep into the lunar interior (Anderson, 1972). However, we do not yet know whether the bulk composition of the Moon is highly depleted in magnesium, which is the major metallic constituent of silicates in the Earth.

If magnesium is not strongly depleted in the Moon, then the logical process for the formation of the Moon is from the hot silicate atmosphere of the primitive Earth. The collision of a fairly massive body with the primitive Earth may set the primitive Earth spinning rapidly enough so that the material in the hot silicate atmosphere is essentially in orbital motion in the equatorial plane beyond about 3 Earth radii. Under such circumstances, the condensation of solids in orbit from the primitive silicate atmosphere may allow the formation of the Moon in the initial equatorial plane of the Earth by an accumulation of these condensates (Ringwood, 1970). A subsequent collision with another somewhat less massive body would then be required in order to tilt the axis of the Earth's rotation with respect to the plane in which the Moon was formed, in order to account for the present observational situation.

If the Moon is strongly depleted in magnesium as well as in iron, then the logical place for its formation is inside the orbit of Mercury. Under the pressure and temperature conditions prevalent there, the only condensates are likely to be calcium and aluminum silicates and titanium oxide. If a body like the Moon were to accumulate fairly rapidly in this region, and if only a slight radial distance further out, a more massive body rich in iron but depleted in magnesium silicates were to form (Mercury), then perturbations of the orbit of the Moon by Mercury may cause it to move outwards in the solar nebula, and subsequent perturbations by Mercury and the Earth may lead to its eventual capture in Earth orbit. It is possible that this is the mechanism which led to the fairly large orbital eccentricity of Mercury (Cameron, 1972).

I have outlined in this article only some of the many consequences which can be deduced from the theory of the massive solar nebula. However, the consequences that I have discussed are perhaps those of greatest interest to earth scientists.

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